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AUTHOR(S)– W. A. Gale

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ABSTRACT

We consider a system for obtaining vertical temperature profiles of the atmosphere from a satellite. A carbon dioxode laser sends a signal which is either tunable over a 2 GHz range or contains a range of frequencies simultaneously. This signal is reflected from the earth's surface or ocean and is received back at the satellite. The returned signal at each frequency is analyzed for absorption due to carbon dioxide in the atmosphere by comparison with a nearby standard. Continuous transmitter tuning is not possible now, but isotopic production of a range of frequencies potentially provides enough information. From absorption as a function of frequency, temperature as a function of altitude can be deduced. The application to co-orbiting satellites is discussed and some laboratory measurements are suggested.

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SUBJECT: Atmospheric Temperature Profiles
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FROM: W. A. Gale

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TECHNICAL MEMORANDUM

INTRODUCTION

The numerical prediction of weather requires an accurate global knowledge of the world's weather at a given time. This is obtained through measurement of pressure at a given altitude, the wind velocity profile with altitude, the temperature profile with altitude, and the water vapor profile with altitude. Currently, reporting of these functions above sea surfaces is sparse, and it seems likely that satellite sensing will be required for adequate coverage. This sensing will make use of the electromagnetic properties of the gases of the atmosphere.

These properties include emission and absorption (or scattering). An operational satellite device(1) utilizes the emission of a strong CO_2 band to obtain the temperature profile. This memorandum describes the use of absorption measurements as an alternative means of obtaining this information. Here, the use of a single broadened absorption line as opposed to a set of lines (or a band) is considered. This is possible by use of a gas laser operating with the same gas as the constituent gas of the atmosphere to be measured. The applications possible with the use of an isotope of the gas to obtain a small known frequency shift, and a laser tunable over a wide enough range of frequencies, are discussed.

We are considering here a system in which the radiation from a carbon dioxide laser is reflected from the ocean, and the return signal is analyzed for absorption. We show below that absorption as a function of frequency is determined by temperature as a function of pressure, and that the latter can be obtained by analysis of measurements of the former.

METEOROLOGICAL REQUIREMENTS

As cited by the Global Atmospheric Research Program,(2) the principal quantities required for numerical weather prediction in the next few years are the four functions:

1.	$p(x,y,z_0,t)$	Pressure at a known altitude. Accuracy required is 2%.
2.	$v(x,y,p,t)$	Wind velocity profile as a function of pressure. Accuracy required is 3 m/sec.
3.	$T(x,y,p,t)$	Temperature profile as a function of pressure. Accuracy required is 1 K.
4.	$q(x,y,p,t)$	Water vapor profile. Accuracy required is 10%.

The range of pressures over which these profiles are desired is from 1000 mb (surface) to 10 mb (∿ 30 km) with 200 mb intervals. The horizontal resolution desired is 400 km intervals in x and y. The time resolution desired is once a day.

The range of temperatures is from slightly below 200 K to slightly above 300 K. The range of velocities is from 0 to 150 m/sec. The range of water vapor fraction is from .00 to .04.

By the late 70's, considerably more demanding requirements will exist -- for finer grids and greater accuracy, especially in the lowest kilometer and beneath clouds. Since the carbon dioxide laser radiation is absorbed by clouds, the considerations in this paper do not apply to complete cloud cover. In a situation of partial cloud cover, the narrow beams used allow data to be obtained in the interstices.

CARBON DIOXIDE AND CO_2 LASER

Carbon dioxide is a linear symmetric molecule, which has three vibration modes. These are

1. symmetric stretch mode ← · →
2. bending mode ↑ ↓ ↑
3. asymmetric stretch mode → ← →

where the arrows show the motions of the three atoms. Each mode can have only an integral number of energy quanta in it, so that a vibration state can be described by a triplet of numbers (n_1 n_2 n_3) indicating the number of quanta in each vibration mode. Laser action is obtained using as the upper energy level (001) and for lower energy level either (100) or (020), giving radiation with wavelength (wave number) of about 10.4μ ($961\ cm^{-1}$) or 9.6μ ($1064\ cm^{-1}$), respectively.(3)

Besides vibrating, the CO_2 molecule can rotate. The rotational quantum of energy is three orders smaller than the vibrational quanta, hence the rotational state modifies the energy levels only slightly, and changes the frequency and wave number of laser radiation slightly. A CO_2 molecule undergoing a vibrational transition either loses one rotational quantum or gains one rotational quantum. In the former case each initial rotation quantum adds .77 cm^{-1} to the central wave number giving rise to the R-branch, while in the latter case, .78 cm^{-1} is subtracted for each initial rotational quantum giving rise to the P-branch. The set of rotational lines about a central vibrational frequency is called a band.(4)

The CO_2 in the atmosphere is thermally distributed among the various energy levels, and will emit or absorb radiation at all the frequencies simultaneously. However, in a CO_2 laser, when one particular rotational line starts lasing, the rapid thermalization time (10^{-7} sec) will deplete other rotational states to refill the one lasing rotational state. The result is that the laser can be made to emit on just one line of the vibrational band.(5) The various frequencies associated with the different rotational states can be obtained in a laser by using a diffraction grating instead of a mirror. Rotation of the diffraction grating then determines which line will lase.(6)

The steady state power of a laser is proportional to the length of the tube. A laser yielding 75 watts/meter has been constructed.(7) By means of alternately exposing and blocking the end diffraction grating or mirror (Q-switching), periods of no lasing can be obtained, during which time energy is stored in the upper level. When lasing is again allowed, the stored energy is all released, giving a pulse. A gain in power of 1000 can be obtained by this means.(8)

LINE SHAPE

Line shape refers to the frequency dependence of absorption or emission of a gas. Typically there is a maximum at one frequency termed line center, with less absorption at higher or lower frequencies. The exact amount less, relative to the maximum, is not only a function of frequency difference from line center, but also of the temperature and pressure of the gas.

At low pressures, the broadening of a line is determined by the Doppler effect: a molecule moving towards a source will absorb radiation of a slightly lower frequency than the natural line position, since *it* sees this frequency as the line center. At high pressures the broadening is determined by collision effects: an individual molecule can only absorb radiation coherently during the time intervals between its collisions, and the finite wave packet thus absorbed may have a considerable range of frequencies represented.

The fraction of energy absorbed at a given temperature, T, pressure, p, and frequency, ω, is denoted $A(p,T,\omega)$. This is related to the absorption coefficient $k(p,T,\omega)$ by the definition

$$1-A(p,T,\omega) = \exp\left(-\int_{\text{path}} k(p,T,\omega)\, d\ell\right).$$

The exponentiated integral is referred to as the optical depth.

The absorption coefficient can be written as the product of the absorption coefficient at line center, and a shape function which contains the dependence on frequency. The shape function attains its maximum value of 1 at line center, ω_0, and falls off to either side reaching 1/2 at $\omega = \omega_0 \pm \alpha$, so that α is the half width at half maximum (HWHM). The shape function depends principally on pressure. The major pressure effect is to determine the HWHM. A minor pressure effect is to modify the functional form of the shape function. In the low pressure region, this functional form is

$$\exp\left(-\left(\frac{\omega-\omega_0}{\alpha_D}\sqrt{\ln 2}\right)^2\right)$$

where α_D is the Doppler half width. In the high pressure region, the functional form is

$$\frac{1}{1+\left(\frac{\omega-\omega_0}{\alpha_L}\right)^2}$$

where α_L is called the Lorentz half width. These functions are plotted for equal half widths in Figure 1. It can be seen that two forms with the same half width differ less from each other than they do from a form with half the half width.

Figure 2 shows the dependence of HWHM on temperature and pressure, as calculated from equations (3-10), (3-26), and (3-30) of Penner.(9) It illustrates the great dependence on pressure in the region of atmospheric parameters shown. In Figures 2 and 3, there are three abscissa scales, one each for temperature, pressure, and altitude, where altitude corresponds approximately to pressure but has no relation to the temperature scale. The range of each scale is the approximate range of the parameters in the atmosphere between 0 and 45 km. To help further, the curves representing functions of pressure are in solid lines, while those representing functions of temperature are dashed. The Lorentz half width is proportional to pressure, while the Doppler half width is independent of it; however, in the atmospheric region of interest, the Lorentz half width dominates, giving the pressure dependence shown.

Figure 3 shows that the absorption coefficient at line center depends exponentially on temperature due to the Boltzmann population of the lower energy state. It has a slight dependence on pressure in the region below 30 km, increasing in pressure dependence to proportional dependence above 30 km.

Thus, roughly speaking, temperature information is contained in the absolute amount of absorption, while pressure information is contained in the relative absorption at different frequencies.

ATMOSPHERIC LINE SHAPE

When a beam of radiation passes through the entire atmosphere it passes through layers with a great variety of temperatures and pressures. In order to sort out the temperature at a given pressure we will use the relative absorption (at different frequencies) that we expect at a given pressure level to isolate the amount of the absorption at that pressure level. From the amount of the absorption, the temperature can be deduced.

Define the following symbols

j	index of pressure level
i	index of frequency
p_j	pressure at level j (chosen by analyst)
T_j	temperature at level j (to be determined)
Δz_j	geometrical thickness of level j (depends on p_j and T_j)
k_j	absorption coefficient at line center for level j (depends on p_j and T_j, see Figure 3)
$t_j = k_j \Delta z_j$	optical thickness of level j at line center assuming 100% CO_2
a_j	fraction of CO_2 in level j

ν_i ith frequency. ν_o is line center.

f_{ij} fraction of line center absorbed at frequency i and level j (line shape) (depends mainly on p_j and ν_i, see Figures 2 and 1).

τ_i measured optical depth at frequency i.

The relation of the indirectly determined quantities to the directly measured τ_i is

$$\sum_j a_j f_{ij} t_j = \tau_i \ . \qquad (1)$$

These equations can be solved for the temperature as a function of pressure by a quick iterative procedure:

(1) The ν_i are determined by the instrument design. Choose discrete values of the independent variable p_j.

(2) Choose a reasonable set of T_j (a standard atmosphere, or the previous day's measurement).

(3) Use the equations represented by Figures 1 and 2 to determine f_{ij}. Note in Figure 2 that the dependence on the assumed T_j is very small.

(4) Assume that $a_j = 3.14 \times 10^{-4}$. (Variations of 2% in this value have been reported. This is on the order of our desired accuracy, and if the report is confirmed, then these measurements might better be used in conjunction with other measurements to determine both carbon dioxide profile and an accurate temperature profile.)

(5) Solve the equations (1) for t_j. In order to solve the equations, the number of measured frequencies must equal or exceed the number of desired pressure levels.

(6) Calculate the altitude of the pressure levels chosen, using the assumed T_j, the equation of hydrostatic equilibrium, and the ideal gas law. From the altitudes determine $\Delta z_j/T_j$ (which is nearly independent of T_j), and hence

$$T_j k_j = t_j/(\Delta z_j/T_j)$$

(7) Use the equations represented by Figure 3 to calculate a new T_j from $(T_j k_j)$.

About two cycles provide convergence, because of the strong dependence of $(T_j k_j)$ on T_j (see Figure 3) compared with the dependence of f_{ij} on T_j (see Figure 2) or the dependence of $\Delta z_j/T_j$ on T_j (independent in the case of a thin layer of ideal gas).

In the above determination of temperature profile, accuracies of 1 part in 300 would be required of the measured quantities since we desire temperature accuracies of that order. However, it is possible to design methods of analysis which include the knowledge we have of the atmosphere at a given place and season. The measurement does not need to be as accurate then, since less information is to be extracted. Using methods of this type, the currently operating system yields useful information from measurements accurate to 1 part in 100. Thus accuracy between 10^{-2} and 10^{-3} seems to be the range that should be designed for.

The "best" choice of frequencies is a subtle mathematical problem which should be addressed elsewhere. Too small a range of frequencies does not give enough difference to the shape factors. Too large a range of frequencies gives only a small attenuation with a relatively large experimental error. Intuitively, the desired range of frequencies should reach a point of rapid change of the shape function while it is not too small: the HWHM at a given pressure is probably close to the optimum frequency shift for measuring the absorption at that pressure. The HWHM for ground level is the largest HWHM occurring in the atmosphere; it is .07 cm^{-1} or 2.1 GHz.

In this section we have shown that measurement of the atmospheric line shape can be interpreted to yield a profile of temperature versus pressure. We have supposed, in effect, that a laser tunable over 2 GHz was available. It may be possible to design such a tunable laser using parametric tuning with tellurium or proustite, but such a laser is not yet available. In the next section we discuss an indirect method of obtaining relative absorptions.

ISOTOPIC TUNING

The carbon dioxide laser can be tuned only 50 MHz from its line center at most, because it stops lasing when pulled from line center by more than the (small) line width of the low pressure CO_2 in the laser. Here I would like to point out a possible means of obtaining a sampling of frequency differences (from line center) in the range up to 2 GHz.

We will show below that several of the carbon dioxide lines have some line of another isotopic variety of carbon dioxide within two gigahertz. If both of these lines are used simultaneously, then their relative absorption by atmospheric carbon dioxide can be determined, since they are so close in frequency that their response to other gases and the ground will be the same. If their frequency difference is δ, this determines the absorption of the atmospheric carbon dioxide at $\omega_{oN}+\delta$, relative to the absorption at the atmospheric line center ω_{oN}. By measuring the relative absorption of each pair of lines within two gigahertz, the same information is obtained as is obtained from the same number of relative absorption measurements at the same set of frequency differences from one given atmospheric line center. The absolute absorption at line center can be obtained by using an isotopic line which is far from line center as a reference frequency. There will be a small amount of absorption of such a reference line (1/2%), but it can be calculated to the overall required accuracy. This information may then be interpreted in terms of meteorological parameters as previously explained.

Now the essential physical requirement for this isotopic tuning to be successful is that several normal carbon dioxide lines should have an isotopic line within two gigahertz. Data have been reported for $C^{12}O_2^{18}$ (hereinafter [12, 18]) which indicate that the (001)→(020) band center is at 967.4 cm^{-1},(10) quite close to the 961.0 cm^{-1} band center for (001)→(100) of $C^{12}O_2^{16}$ (likewise referred to as [12, 16]). Figure 4 shows the laser lines available from these two varieties of carbon dioxide. Two gigahertz is about the width of the marks shown. The frequency differences between lines of each type of carbon dioxide are known to great accuracy, but the overall alignment of the two sets of lines is uncertain to about two gigahertz. (That is, the two sets of lines can be shifted with respect to each other by about the width of one line and remain within current experimental accuracy.) It can be seen from the figure that between 5 and 10 pairs of lines are within two gigahertz for any possible overall alignment. Calculations indicate that [12, 17] will also have its two bands in the same regions, and more near coincidences should be expected from this. Since the exact differences are not available now, it is not possible to state whether the available pairs will provide a basis for significant weather information.

Immediate laboratory measurements can resolve uncertainty in this regard. The frequency differences for each pair would be readily measurable using two lasers, or one isotopically enriched laser. Furthermore, the same apparatus should be used to measure the absorption of the [12, 16] member of the pair of lines as a function of pressure. This would give accurate measures of the Lorentz half width for particular rotation states. From these, interpolation to other rotation levels would greatly improve the (one figure) accuracy now available.

SIGNAL, NOISE, AND BACKGROUND

We now consider the system characteristics for detecting one second of laser emission from a satellite, which is reflected from the ocean, and received back at the satellite. The laser system for which the signal and background are figured is considered to be similar to the system to be flown on the ATS-F. In this system the received frequency modulated laser signal is mixed with a laser local oscillator and the difference frequency detected in a square law detector. The advantage of this system is that the detector used can be at a high enough (100 K) temperature that it can be radiation cooled, while detecting 7×10^{-7} erg/sec(10) with bandwidth 1 MHz. This means that for given bandwidth B in Hertz, the noise level is $N = 7 \times 10^{-13}\ B$ erg/sec. Since 1 MHz is the long term frequency(11) stability of current lasers, we will assume this is the necessary bandwidth.

In our case the signal is supposed to have been transmitted by a laser, reflected from the earth or ocean, and then received. If the transmitted signal is frequency modulated, then the reflected signal will be also. The signal is attenuated by (1) passage through the atmosphere twice (50% attenuation each way), (2) reflection from the ocean or land (1% reflection coefficient), (3) spreading into 2Π steradians by the roughness of the reflecting surface. The <u>background</u> is 300 K blackbody radiation:

$$N_B = 4 \times 10^{-9}\ AB\Omega \text{ erg/sec}$$

$$\Omega = (\lambda/D)^2 = \lambda^2/(4A/\Pi)$$

$$N_B = 3 \times 10^{-9}\ B\lambda^2 \text{ erg/sec}$$

$$= 3 \times 10^{-15}\ B \text{ erg/sec}$$

where A is area (cm^2) of receiving mirror with diameter D (cm)

B is bandwidth in hertz (10^6)

λ is wavelength in cm (10^{-3})

Ω is the field of view (sr).

Hence this is much less than the detector <u>noise</u> of 7×10^{-13} B erg/sec and the background is negligible.

We now consider the use of pulsed (P) or continuous wave (CW) radar employing the standard concepts of radar in the same situation.(12) As indicated above, the noise is

$$N = 7 \times 10^{-13} \text{ B erg/sec}$$

where

B is the bandwidth in hz.

A CW signal has a coherence time of 1/B. During this time interval the signal to noise becomes S_{CW}/N, where, considering the attenuation discussed above,

$$S_{CW} = P_t(.5)^2(.01)(A/2\Pi H^2)$$

in which P_t is the transmitted power

H is the satellite altitude.

For the most optimistic values of

P_t = 50 watts

A = 10^4 cm^2

H = 250 km

we obtain $S_{CW} = 3 \times 10^{-6}$ erg/sec.

In one second, averaging B independent samples, the signal to noise is

$$\left.\frac{S_{CW}}{N}\right)_{1sec} = \sqrt{B}\left.\frac{S_{CW}}{N}\right)_{1/B\ sec} = \sqrt{B}\ \frac{3\text{x}10^{-6}}{7\text{x}10^{-13}\ B} \cong 4 \times 10^3$$

for B = 10^6 hz. This S/N exceeds that required (see page 7 above) by a factor of from 4 to 40. We note that when a narrower bandwidth (laser stability) can be designed, the signal to noise can be increased.

Consider now a pulsed signal which has S_P=g S_{CW}, and has the same average power and bandwidth as a CW system. The pulse length is T = 1/B, or 10^{-6} sec in this case. The number of pulses per second, n, is given by gnT = 1. For the carbon dioxide laser, we have seen that g = 10^3 has been obtained, so that n = 10^3 pulses/sec. Now the signal to noise for each pulse is $S_P/N = g\ S_{CW}/N$, and for 1 sec the signal to noise ratio is

$$\left.\frac{S_P}{N}\right)_{1sec} = \sqrt{n} \quad g \quad \left.\frac{S_{CW}}{N}\right)_{Tsec} = 10^{1.5} \times 10^3 \times 5$$

$$= 1.5 \times 10^5$$

This S/N is substantially larger than the required 10^2 to 10^3. In this case an improvement cannot be made by decreasing the bandwidth, because the duration of the pulse is reaching a maximum which can be provided as a pulse by the laser.

For the present technology, at which a bandwidth of 1 MHz is the least that can be used, the pulsed system offers a greater signal to noise ratio. On the other hand (a) the signal to noise of the CW system is entirely adequate for our purposes, and (b) it is not clear that the noise for the pulsed system would be as low as that quoted for the operational CW system.

I should like to point out here that a world wide grid of corner reflectors would allow a substantially increased signal to noise for either CW or pulsed performance. If the corner reflectors have area A_2, while the satellite telescope has area A_1, then the attenuation of the signal returned to the satellite will be

$$\frac{A_2}{\Omega H^2} \cdot \frac{A_1}{\Omega H^2}$$

With $A_2 = 1\ m^2$, $\Omega = 3 \times 10^{-9}$ sr, $H = 250$ km, this gives

$$10^{-5} A_1 \quad (A_1 \text{ in } m^2)$$

compared to rough reflection attenuation of

$$A_1/2\Pi H^2 = 1.6 \times 10^{-11} A_1 \ .$$

It can be seen that ideally a factor of 10^6 in S/N could be obtained for any given size satellite mirror. This probably means that even with marine degradation of the corner reflectors (three-fourths of these stations would have to be at sea), a significant improvement could be obtained. The practical limitations would probably be satellite stability and pointing accuracy, and dependence on the cloud state above the reflector.

USE ON CO-ORBITING SATELLITES

Co-orbiting satellites are two (or more) satellites with the same orbit, but differing in phasing around the orbit. In meteorological use, the phasing would be arranged so that the line between the two passed through the atmosphere with a chosen minimum altitude. By the geometry of the path, its greatest length in a given thickness of atmosphere is in the lowest such layer. Measurements made along this path thus allow almost direct inference of conditions in the lowest part of the atmosphere reached.

Development of the technology of co-orbiting satellites has been urged for many meteorological applications.(13) Their principal advantage is that altitude is a direct geometrical interpretation rather than such indirect inference as described in this paper. Also, absorption or transmission measurements become possible without using any ground station.

Even without the development of wide range tuning of the carbon dioxide laser, there are two ways temperature could be determined from co-orbiting satellites. The first method is the measurement of the absolute absorption by comparison of any given line of [12, 16] with a nearby reference line. We have seen (Figure 3) that line center absorption is a strong function of temperature. This measurement also depends on the amount of carbon dioxide present.

A second method is to compare the relative absorption of two rotation lines. Since the rotation states are occupied in a Boltzmann distribution, the relative absorption will indicate the relative occupation, and hence the temperature.

If both measurements were made, both temperature and carbon dioxide concentration could be unambiguously derived.

A modest system could make absorption measurements between 9 km and many tens of kilometers. Consider a 1 watt transmitter with 10 cm diameter mirrors for sending and receiving. If the satellites are in 250 km earth orbit, they will be about 3500 km apart, and the received signal in the absence of atmospheric attenuation would be about 1 erg/sec. Hence, atmospheric transmissions as low as 3×10^{-6} can be tolerated for $S/N)_{1sec} = 10^3$. This level of transmission is reached on the path with lowest point about 9 km altitude. As the altitude is increased, the absorption decreases. The accuracy of the absorption determination will then decrease, since it is a deduction from the measured transmission, which is approaching unity with a fixed accuracy. In the region of small absorption, the accuracy of the absorption measurement is limited by the accuracy of the reference signal. We have not discussed the accuracy of the reference signal, but supposed that it is at least 10^{-3}. Thus we expect to maintain 10^{-3} accuracy on absorption until somewhere in the region from 50 to 70 kilometers, where the tangential absorption decreases from 0.9 to 0.1.

SUMMARY

We have considered a system in which carbon dioxide laser is used to send a pulse to be reflected from the ocean, then received and analyzed for the absorption due the atmosphere. We have shown that the ideal signal to noise obtainable for such a system is large enough to indicate an actual engineering possibility. We have shown how the information on temperature as a function of pressure is transformed into information on absorption as a function of frequency and how measurements of the latter can yield the former. We have indicated means of obtaining frequency spread, though it is difficult. We have also considered, qualitatively, the use of a carbon dioxide laser on co-orbiting satellites.

Compared with present systems, the herein suggested system has the principal advantage of growth potential. When larger signal to noise ratio is required, the present system can increase mirror size. The suggested system on the other hand, can increase mirror size, increase power, or decrease bandwidth. The suggested system is probably more expensive. In general, the level of performance at which the suggested system becomes competitive with the present system is an economic question, which we have not addressed here. Neither system can obtain information below continuous cloud tops, but the suggested system, using a narrow beam may be able to get information from between scattered clouds.

Further investigation of this device should examine (1) possible ways of obtaining 2 GHz frequency tuning, and (2) detailed comparison with existing systems. Certain parameters of interest could be readily measured if isotopic CO$_2$ lasers capable of tuning across their rotation spectra were available: (1) absorption at line centers at a standard temperature and pressure, (2) frequency differences between nearby pairs of lines of different isotopes, and (3) accurate measures of the Lorentz half width of the standard atmospheric lines.

William A. Gale

1011-WAG-caw W. A. Gale

Attachments
References
Figure Captions
Figures 1-4

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FIGURE CAPTIONS

Figure 1: Comparison of forms of relative absorption for pressure broadened and Doppler broadened lines. Also shown is a Doppler form with half the line width of the other two.

Figure 2: Dependence of line width on pressure and temperature. The pressure scale is logarithmic while the temperature scale is linear, so that each shows the range of the parameter in the atmosphere up to 45 km altitude. The line width clearly depends more on the pressure than on the temperature.

Figure 3: Dependence of absorption coefficient on pressure and temperature. The abscissa scales are the same as Figure 2. Here the greater dependence is on the temperature.

Figure 4: The two lasing bands obtained in each of two isotopic varieties of carbon dioxide. The number labeling each line in the bands is the rotational quantum number of the initial molecular state. The circles point out nearly overlapping lines. The relative position of the two series is uncertain to about the thickness of the lines on the figure. The desired tuning range is the same magnitude. Depending on the relative shift of the two sets of lines, between five and eight of the pairs will be in the tuning range desired.

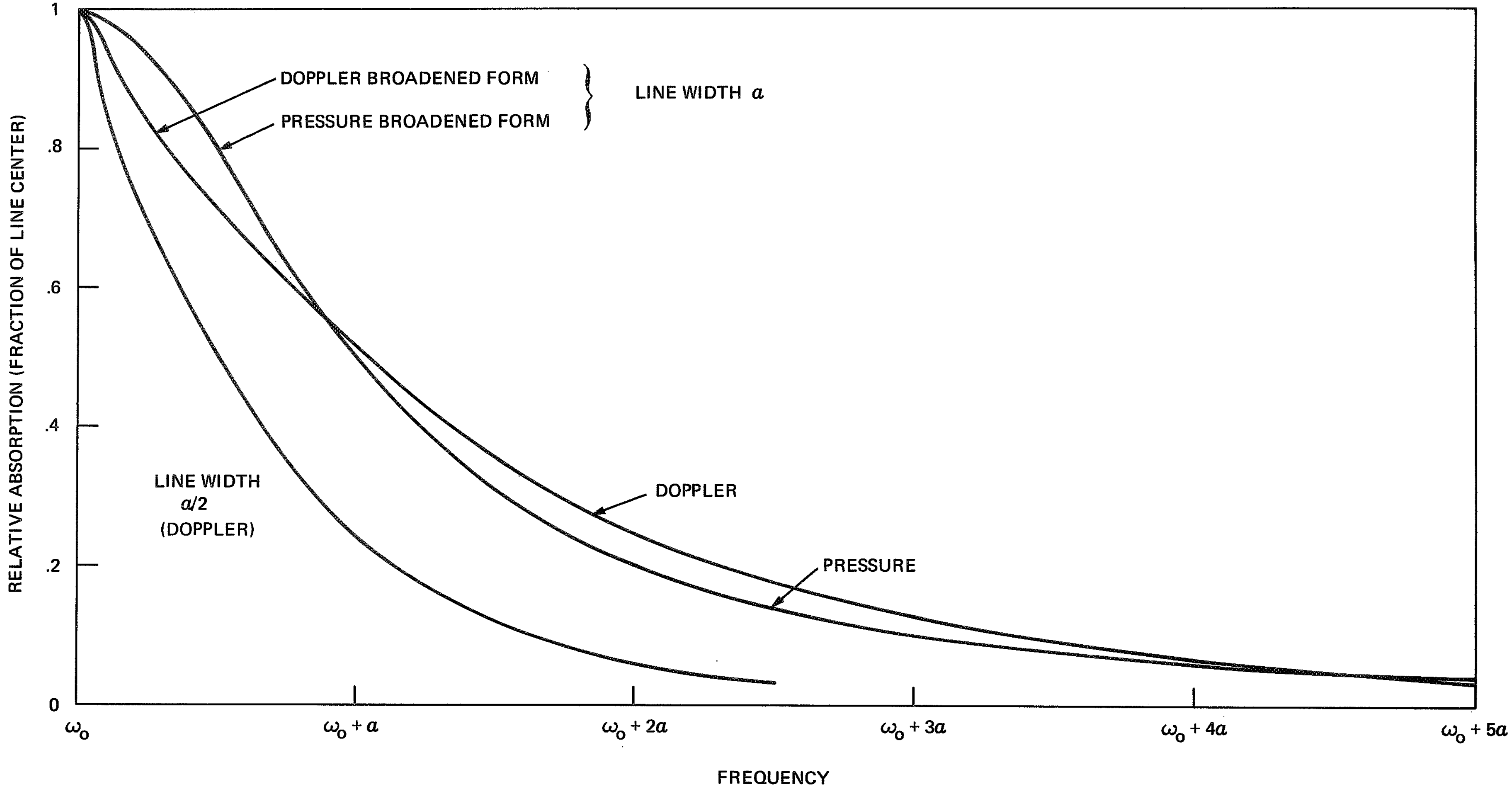
1
.8
.6
.4
.2
0
RELATIVE ABSORPTION (FRACTION OF LINE CENTER)
DOPPLER BROADENED FORM
PRESSURE BROADENED FORM
LINE WIDTH a
LINE WIDTH
$a/2$
(DOPPLER)
DOPPLER
PRESSURE
ω_o
$\omega_o + a$
$\omega_o + 2a$
$\omega_o + 3a$
$\omega_o + 4a$
$\omega_o + 5a$
FREQUENCY

FIGURE 1

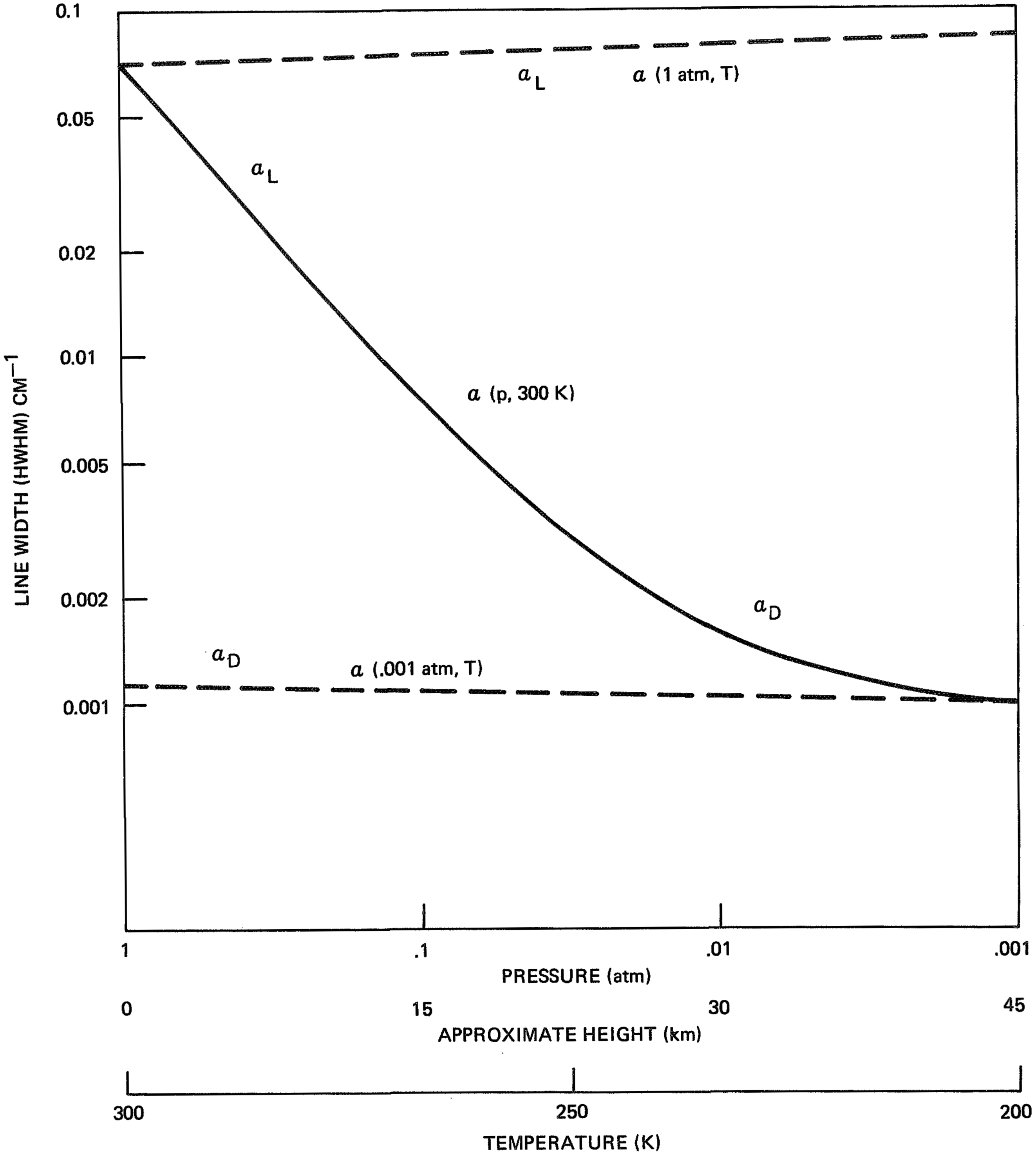
0.1
0.05
0.02
0.01
0.005
0.002
0.001
LINE WIDTH (HWHM) CM^{-1}
a_L
a (1 atm, T)
a_L
a (p, 300 K)
a_D
a_D
a (.001 atm, T)
1
.1
.01
.001
PRESSURE (atm)
0
15
30
45
APPROXIMATE HEIGHT (km)
300
250
200
TEMPERATURE (K)

FIGURE 2

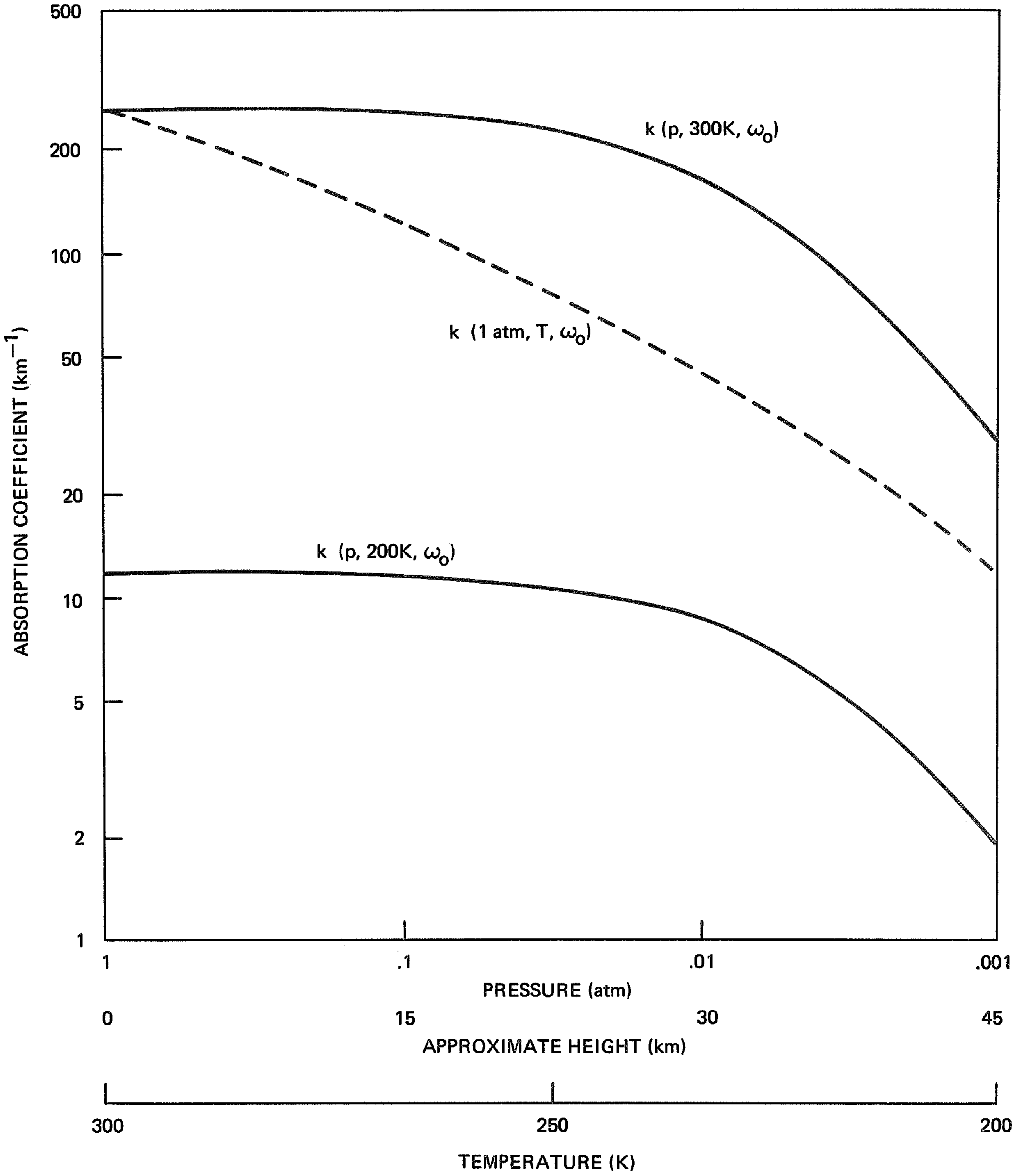
500
200
100
50
20
10
5
2
1
ABSORPTION COEFFICIENT (km^{-1})
k (p, 300K, ω_o)
k (1 atm, T, ω_o)
k (p, 200K, ω_o)
1
.1
.01
.001
PRESSURE (atm)
0
15
30
45
APPROXIMATE HEIGHT (km)
300
250
200
TEMPERATURE (K)

FIGURE 3

NEARBY LASING LINES
FROM TWO ISOTOPES OF CARBON DIOXIDE

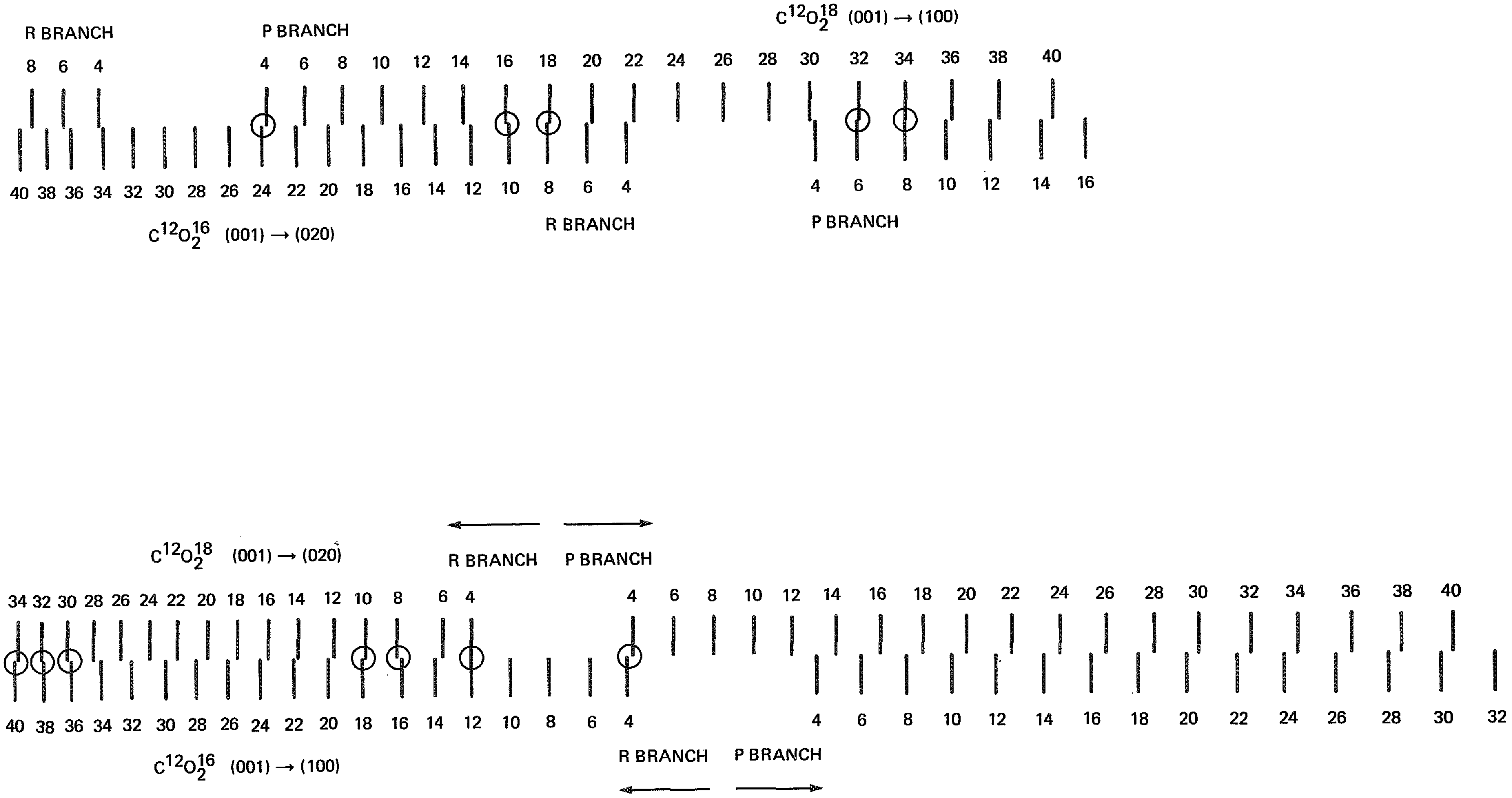

FIGURE 4